Exploring Strongly Interacting Matter Under Extreme Conditions

a brief overview of research activities of

BNL Lattice Gauge Theory Group

Swagato Mukherjee

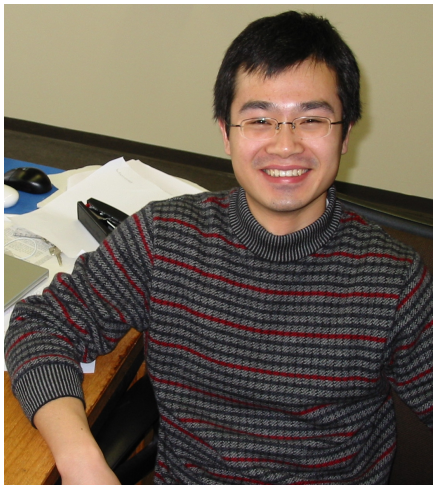
on behalf of the BNL LGT group

March 2013, Brain Circulation Workshop, BNL

Who are we?

present members

Alexei Bazavov



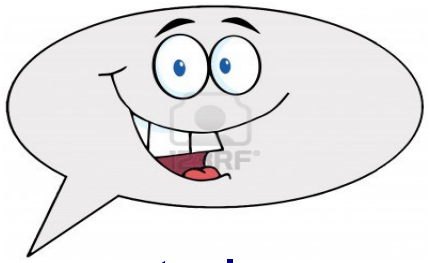
Heng-Tong Ding

Chulwoo Jung

Frtihjof Karsch

our leader

Yu Maezawa

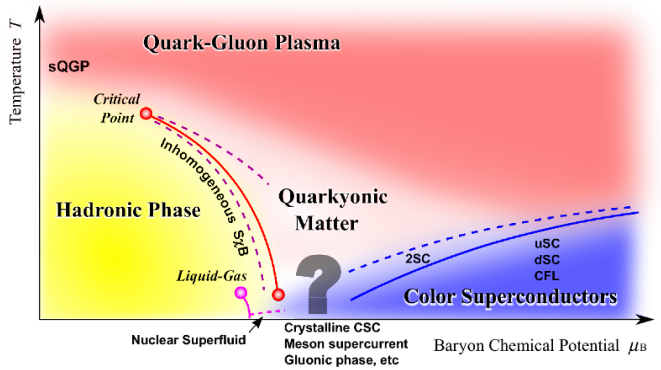


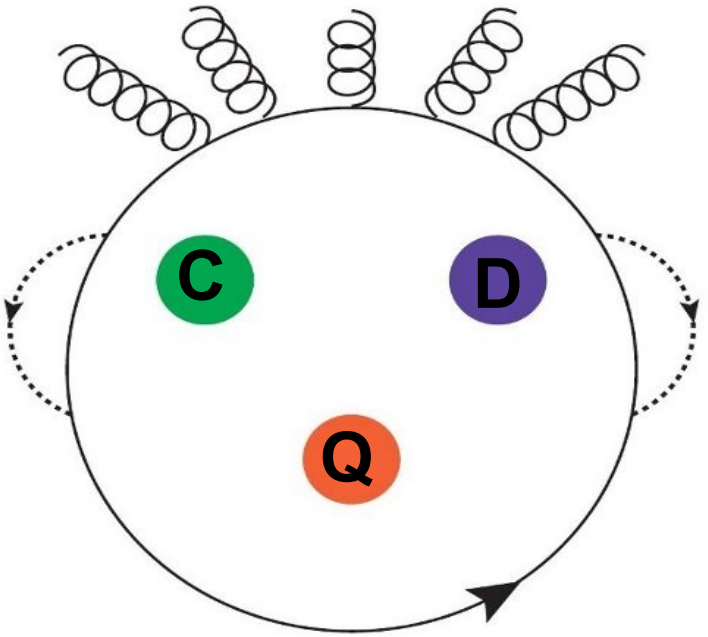
yours truly

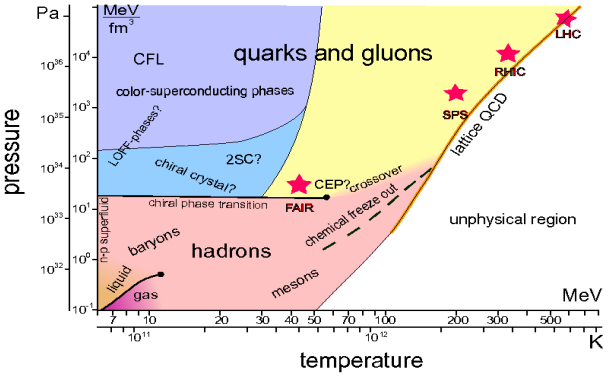
Peter Petreczky

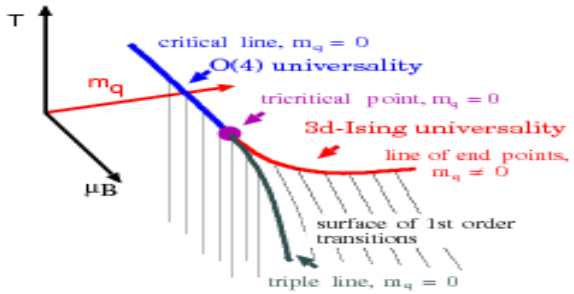
What do we do ?

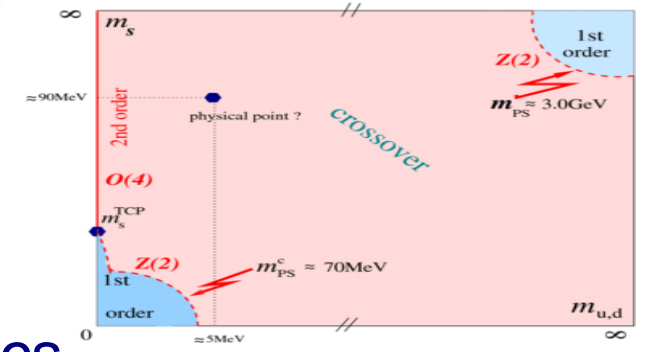
explore phases of the theory of strong interaction











Quantum Chromo Dynamics

under extreme conditions

high temperatures

high densities

small quark masses

high magnetic fields

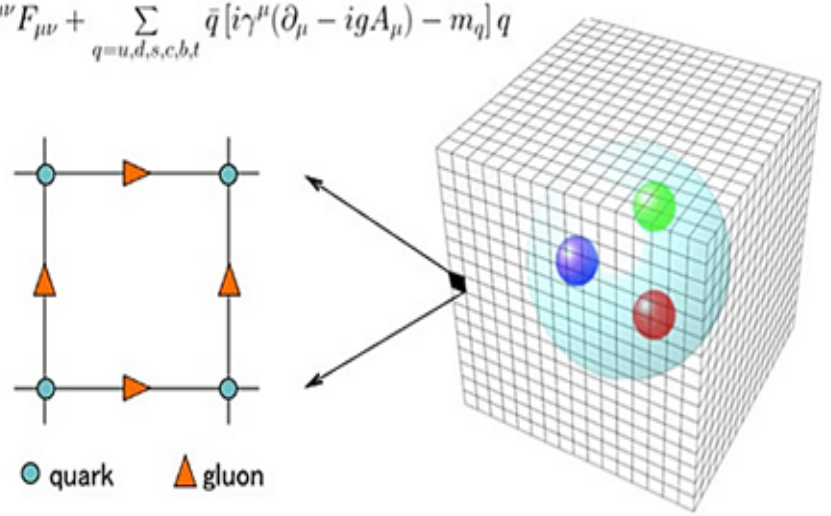
. . .

How do we do it ?

Lattice QCD

QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA_{\mu}) - m_q\right]q$$



put QCD on a discretized (Euclidean) space-time lattice

perform path integral numerically using Monte-Carlo technique

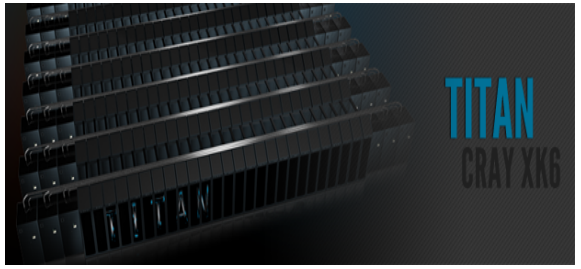
ab-initio and non-perturbative

How do we do it ?

Lattice QCD

large computers ...

top 500 rank: 1



Titan @ ORNL

top 500 rank: 2

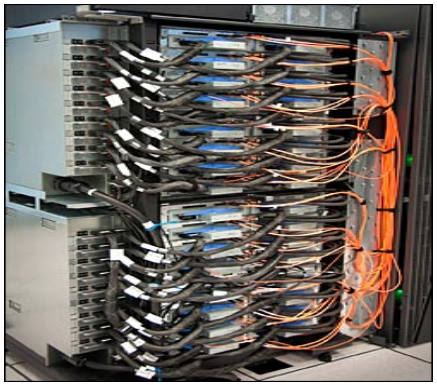
Sequoia @ LLNL

top 500 rank: 4

Mira @ ANL

top 500 rank: 5

JuQeen @ Juelich

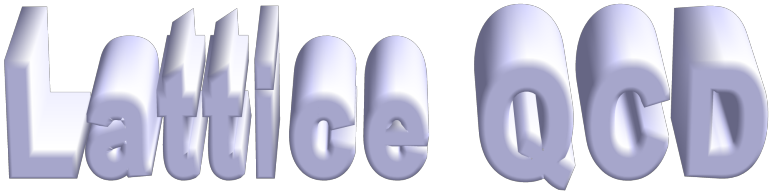


QCDCQ @ BNL

GPU-cluster @ Bielefeld

10g @ Jlab

How do we do it ?



… and even larger pool of brains

Bielefeld University, Germany

Columbia University, USA

HotQCD

RIKEN-BNL

USQCD

… and many others

Our laundry list ...

equilibrium & near-equilibrium properties
of QCD under extreme conditions
relevant for heavy ion collision experiments

as well as fundamental theoretical issues

- chiral and deconfinement crossover at high temperatures / non-zero densities / high magnetic fields
- nature of the chiral transition & its influence on the physical point
- QCD phase diagram as a function of quark masses
- fate of axial anomaly in the chirally symmetric phase
- QCD equation of state at high temperatures and non-zero densities
- degrees of freedom in high temperature QCD
- QCD phase diagram in the temperature-(baryon) density plane
- freeze-out conditions of heavy ion collisions
- dilepton / photon emissivity of quark gluon plasma
- fate of quarkonia inside quark gluon plasma
- thermalization of charm quarks: charm quark diffusion constant
- and more ...

Our laundry list ...

equilibrium & near-equilibrium properties
of QCD under extreme conditions

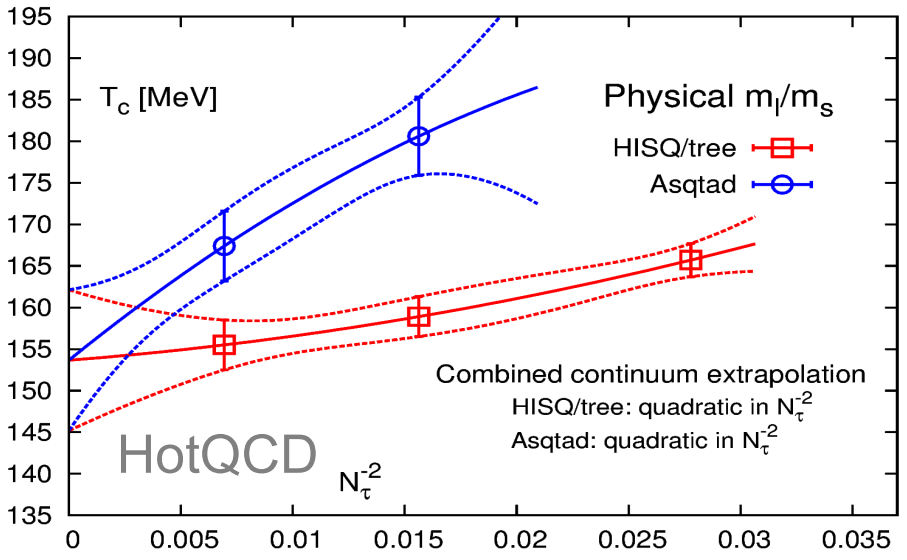
relevant for heavy ion collision experiments

as well as fundamental theoretical issues

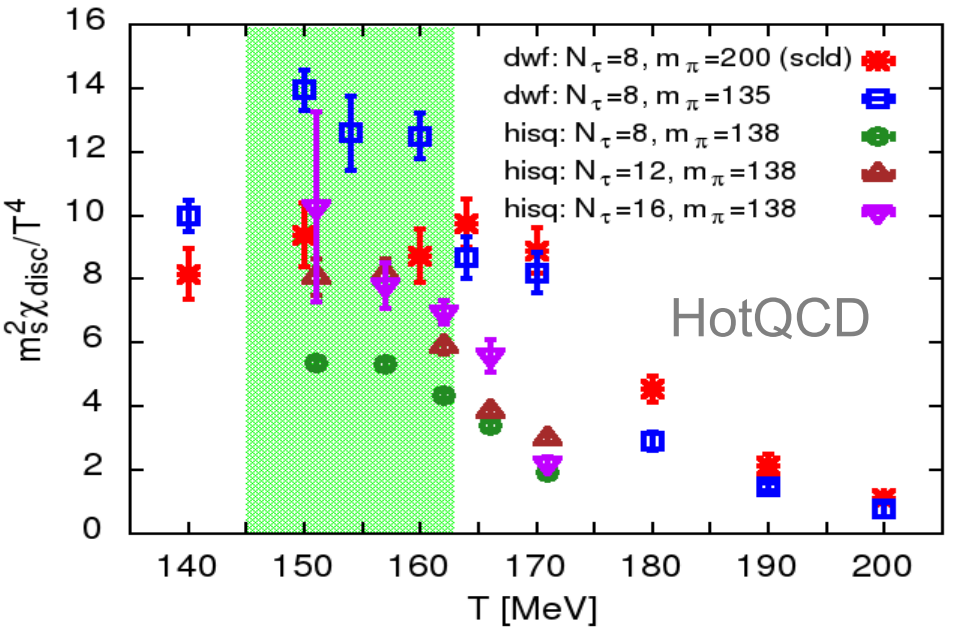
can not cover any of these in details, our apologies ...

just show a few random pages from our scrapbook ...

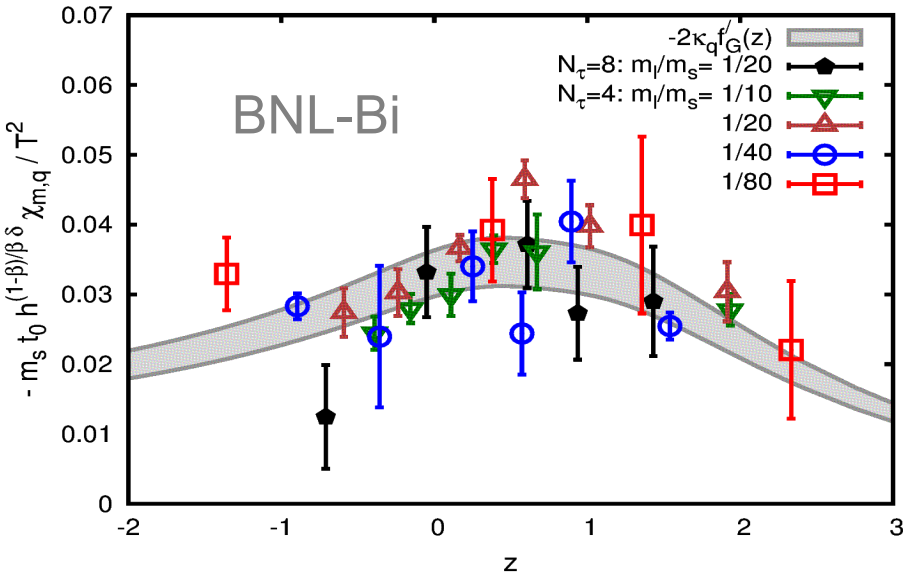
Chiral crossover line in the $T-\mu_B$ plane



Highly Improved Staggered Quarks



Chiral (Domain Wall) Fermions

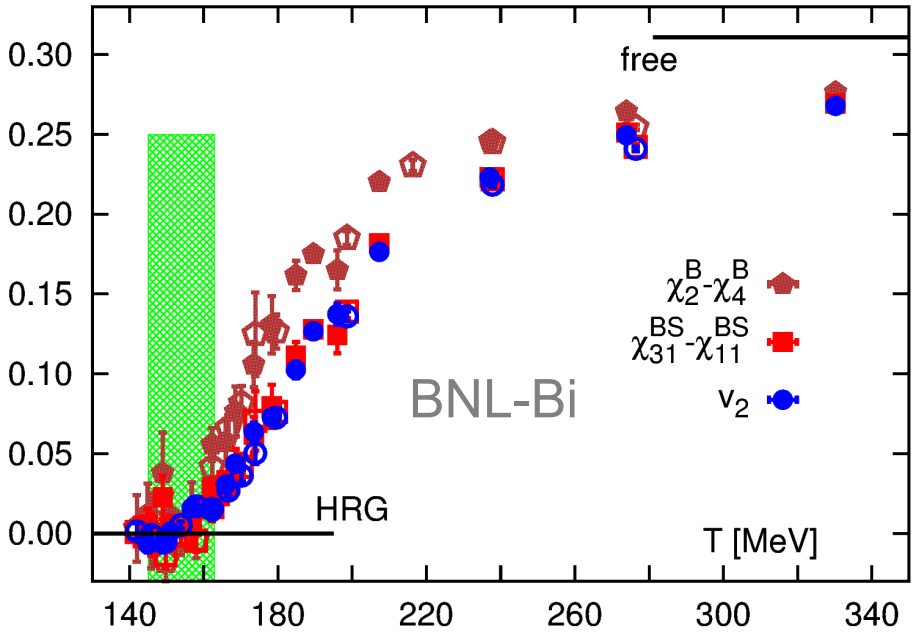


chiral crossover

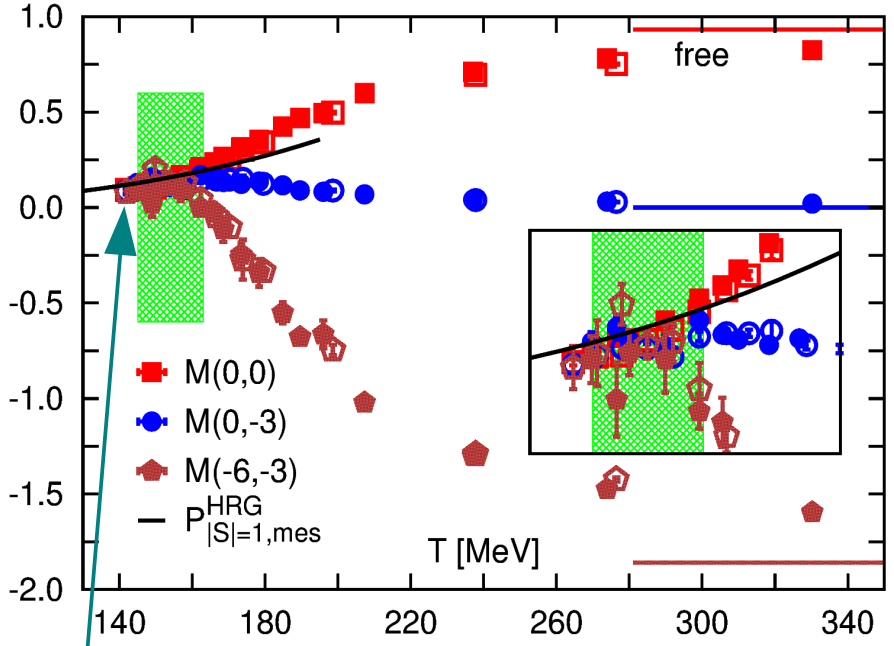
$$T_c = 154(9)\ \text{MeV}$$

$$T_c(\mu_B) = T_c\left[1 - 0.0066(7)\left(\mu_B/T_c\right)^2\right]$$

Deconfinement and the chiral crossover



light and strange baryon fluctuations



strangeness fluctuations

partial pressure of strange mesons in HRG

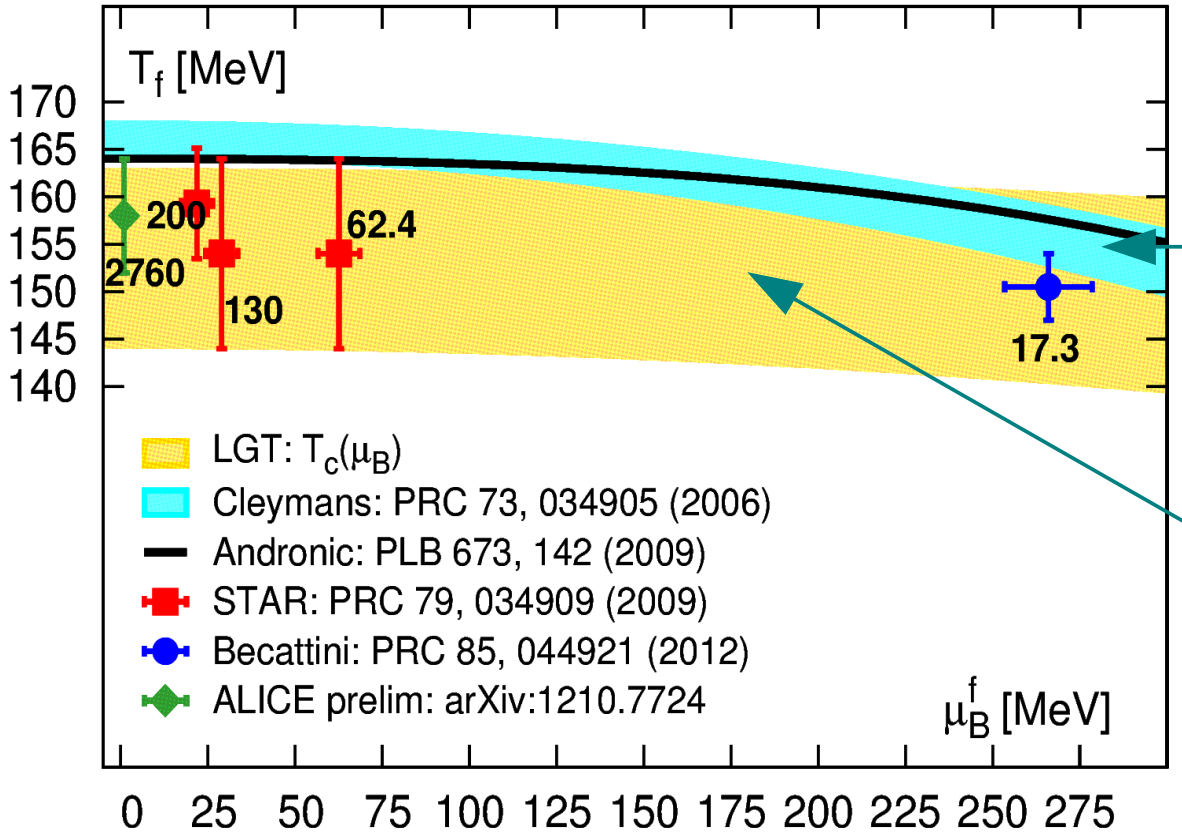
good description in terms of hadron resonance gas up to the chiral crossover temperature

dramatic break down of hadron resonance gas just above the chiral crossover temperature

same for light and strange quarks

deconfinement happens at the chiral crossover ?

Freeze-out in HIC and the crossover line



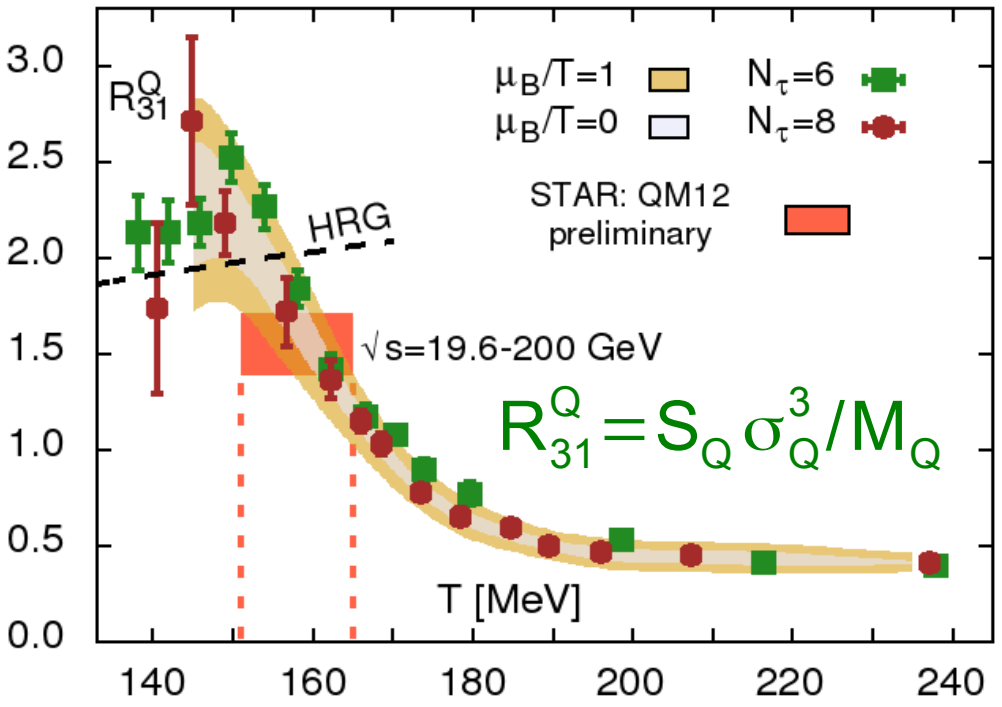
chemical freeze-out
in heavy ion collisions

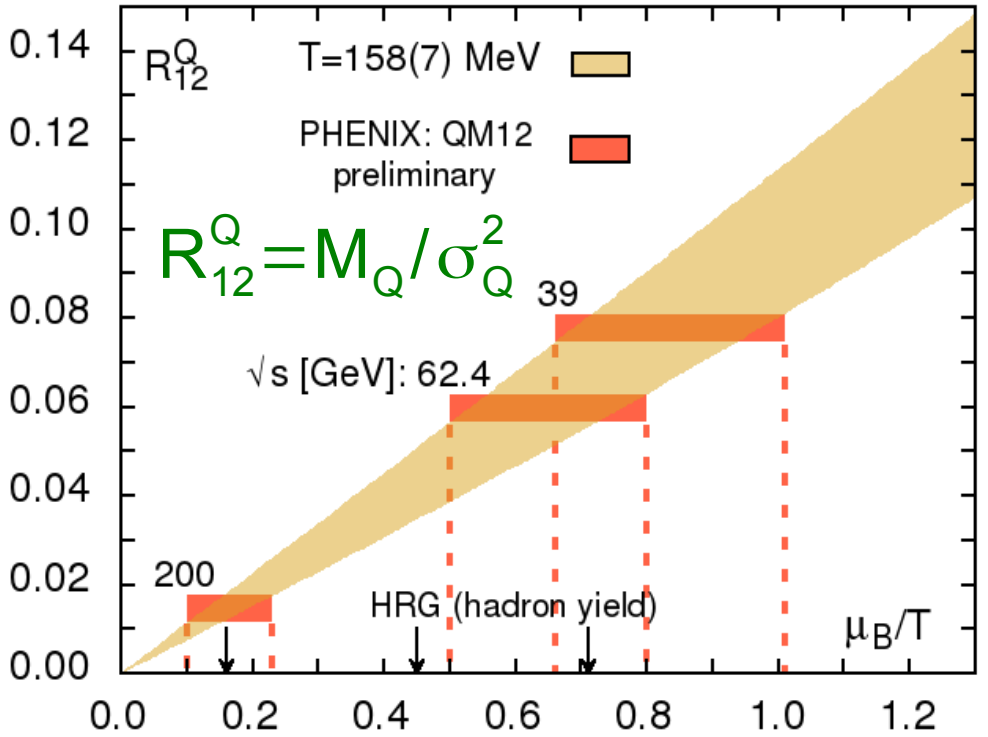
from statistical hadronization/
hadron resonance gas model

crossover line
from Lattice QCD

freeze-out conditions in heavy ion collisions
from first-principle Lattice QCD ?

Freeze-out of charge fluctuations: LQCD and HIC experiments





BNL-Bi

higher cumulants of net charge fluctuations

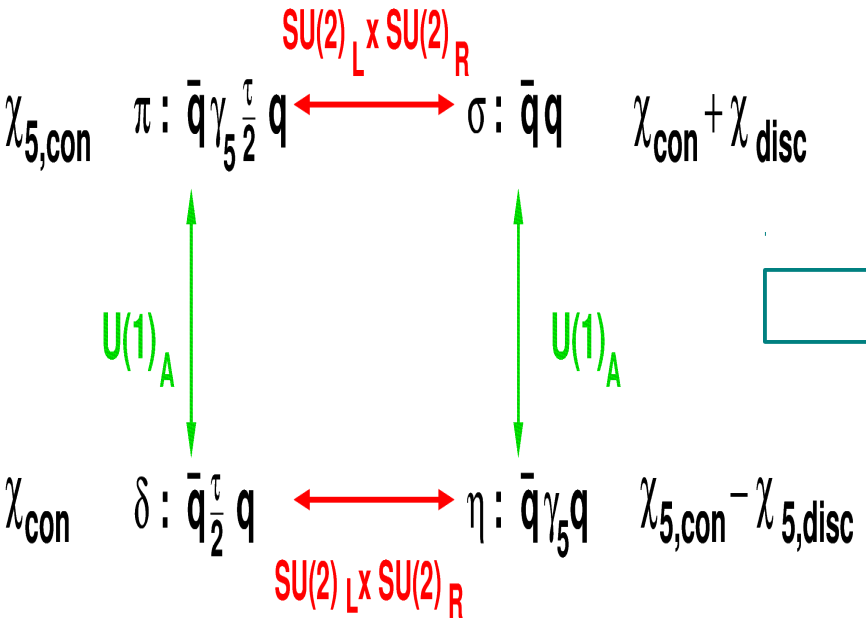
mean: M_Q, variance: σ^2_Q, skewness: S_Q

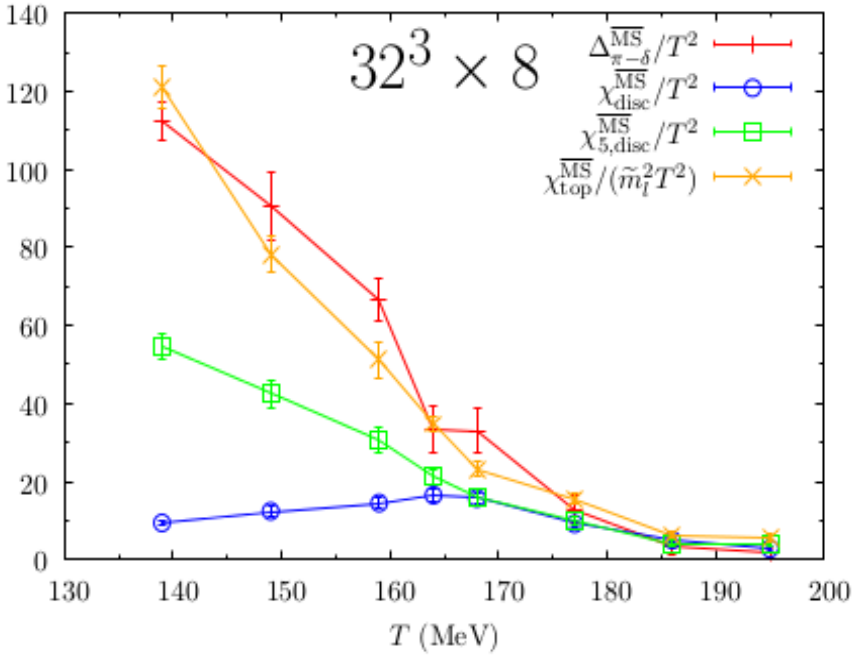
freeze-out conditions in HIC from LQCD

general agreement with chemical freeze-out parameters
obtained from thermal model fits to hadron yields

Fate of axial anomaly in quark gluon plasma

quantifying axial symmetry breaking in QGP





$$\chi_\pi - \chi_\delta = \chi_{\rm disc} = \chi_{5,\rm disc} = \frac{\chi_{\rm top}}{m_l^2}$$

$T > T_c$, $m_l \to 0$

Chiral (Domain Wall) Fermions

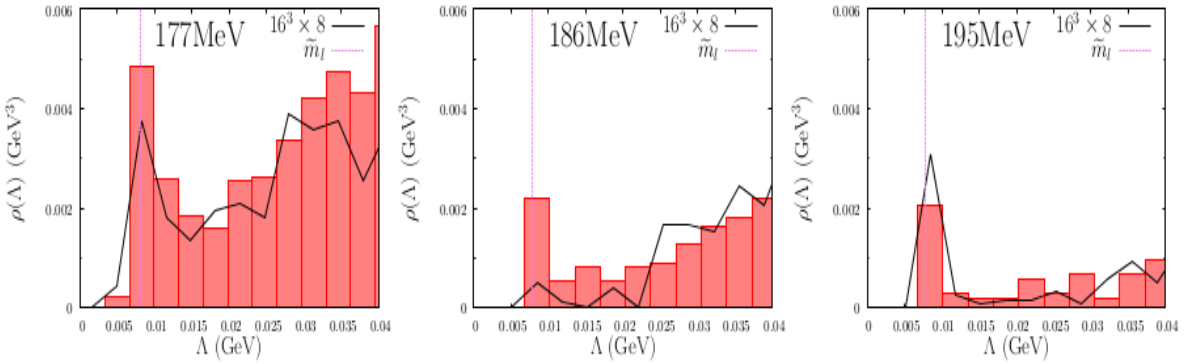
RIKEN-BNL-Columbia

Fate of axial anomaly in quark gluon plasma

mechanism of axial symmetry breaking in QGP

eigenvalue distribution of the Dirac operator

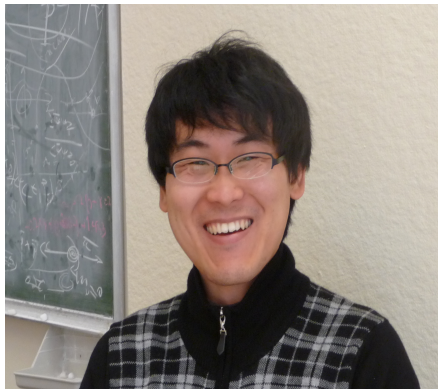
Chiral (Domain Wall) Fermions



$$\rho(0) \sim m_l^2 \delta(\lambda) \; ?$$

RIKEN-BNL-Columbia

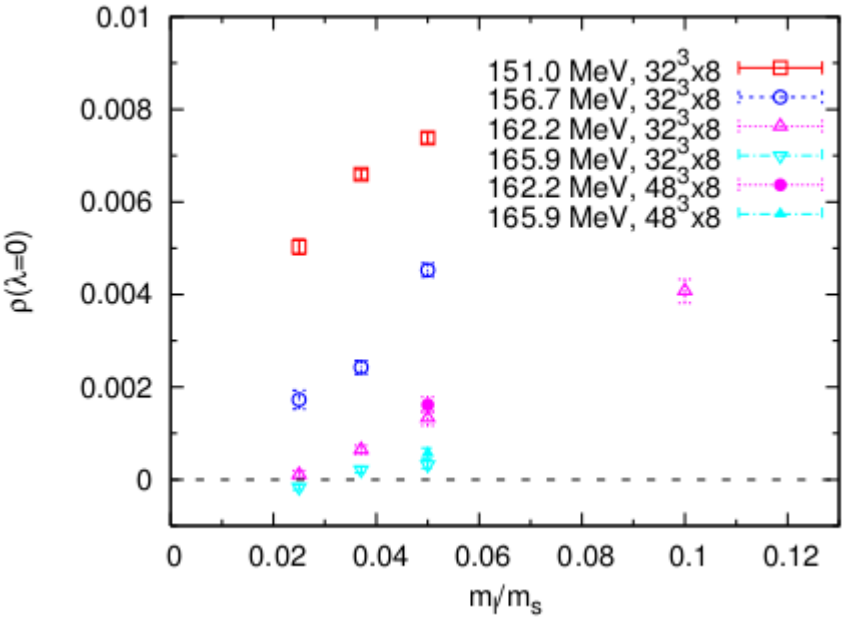
courtesy



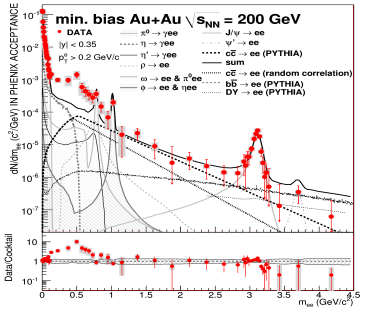
Hiroshi Ohno

$$\rho(0) \sim |m_l| \; ?$$

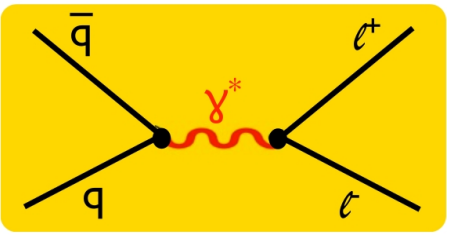
Highly Improved Staggered Quarks

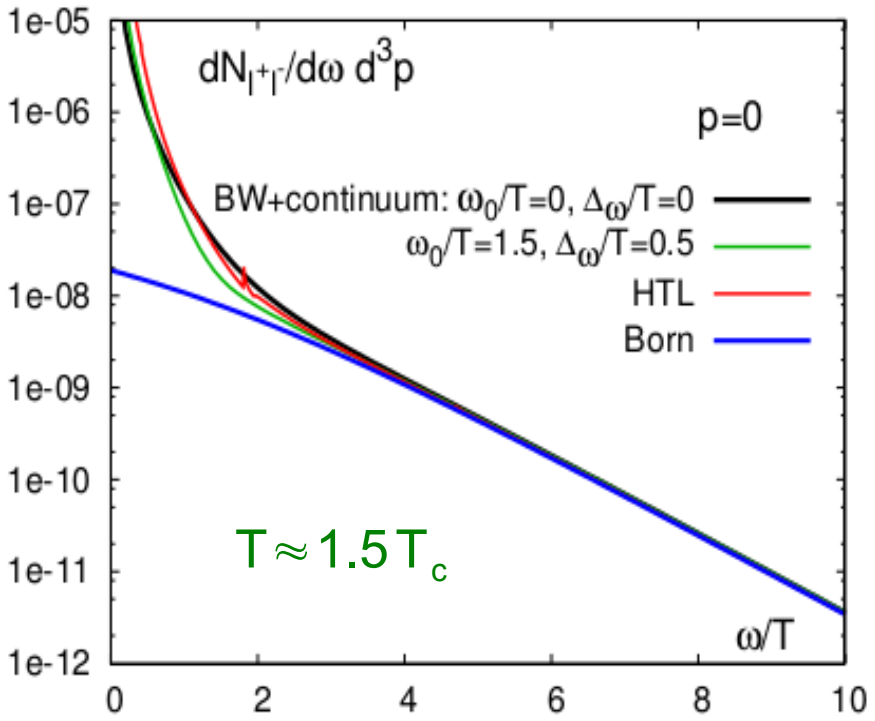


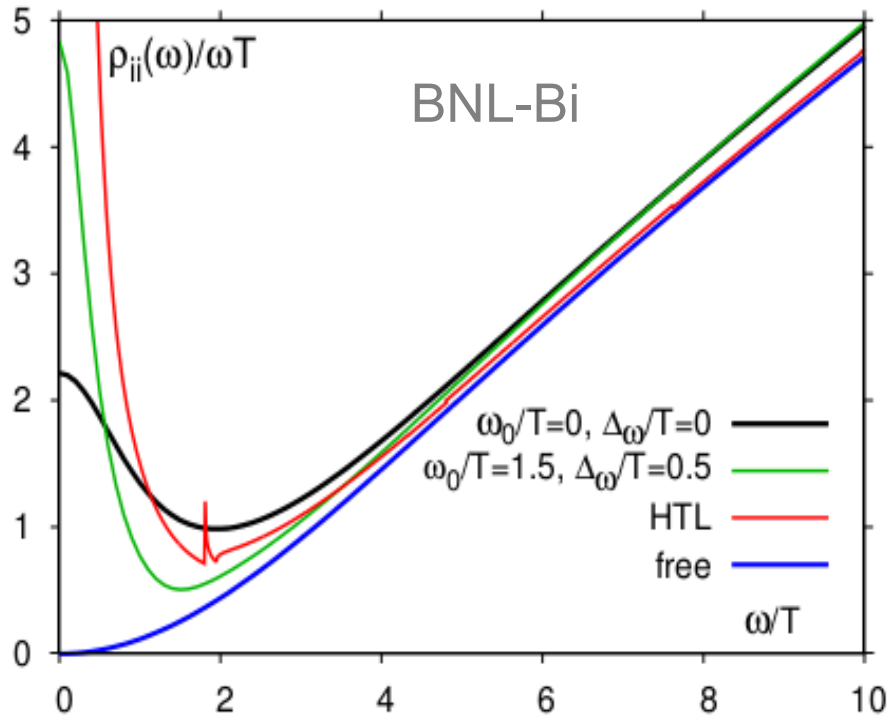
Dilepton emissivity of QGP



thermal dilepton rate and electrical conductivity





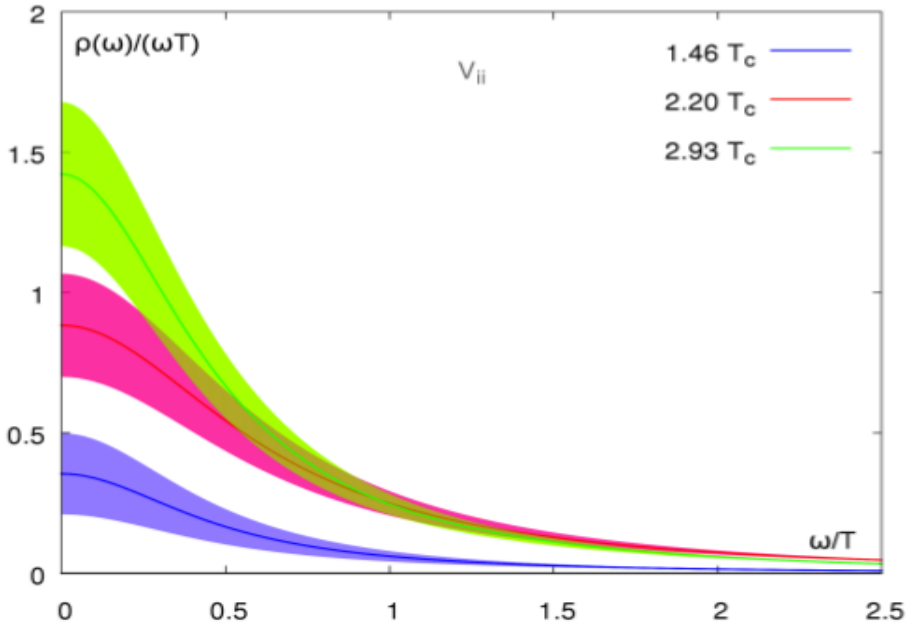


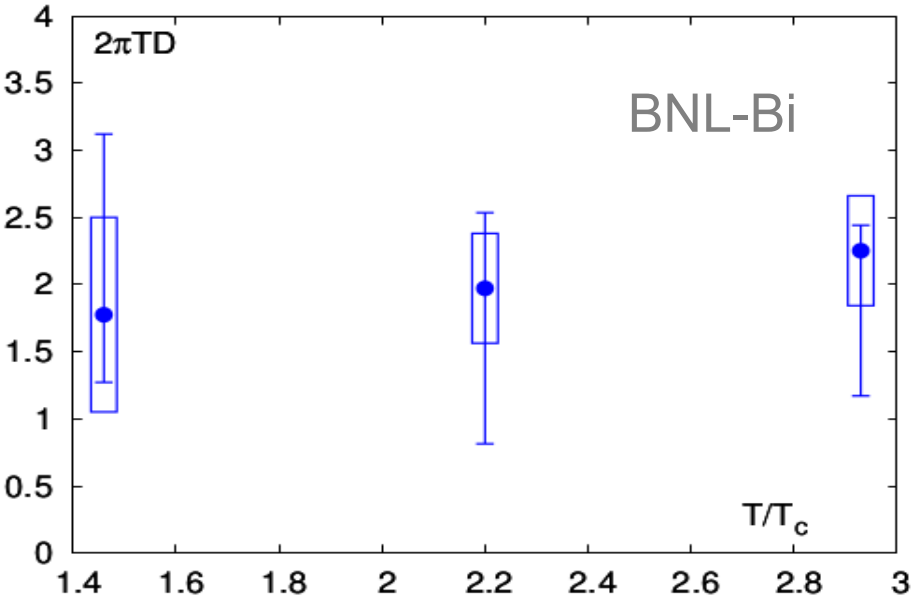
electrical conductivity of QGP: $C_{em}/3 \lesssim \sigma/T \lesssim C_{em}$

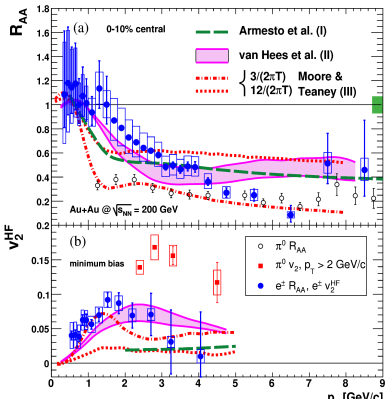
$$C_{em} = \sum_f q_f^2, \quad T \approx 1.4\, T_c$$

Charm and charmonia at high temperatures

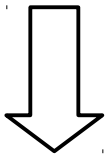
spatial diffusion constant of charm quarks inside QGP







smallness of the charm diffusion constant



thermalization of charm quarks inside QGP ?

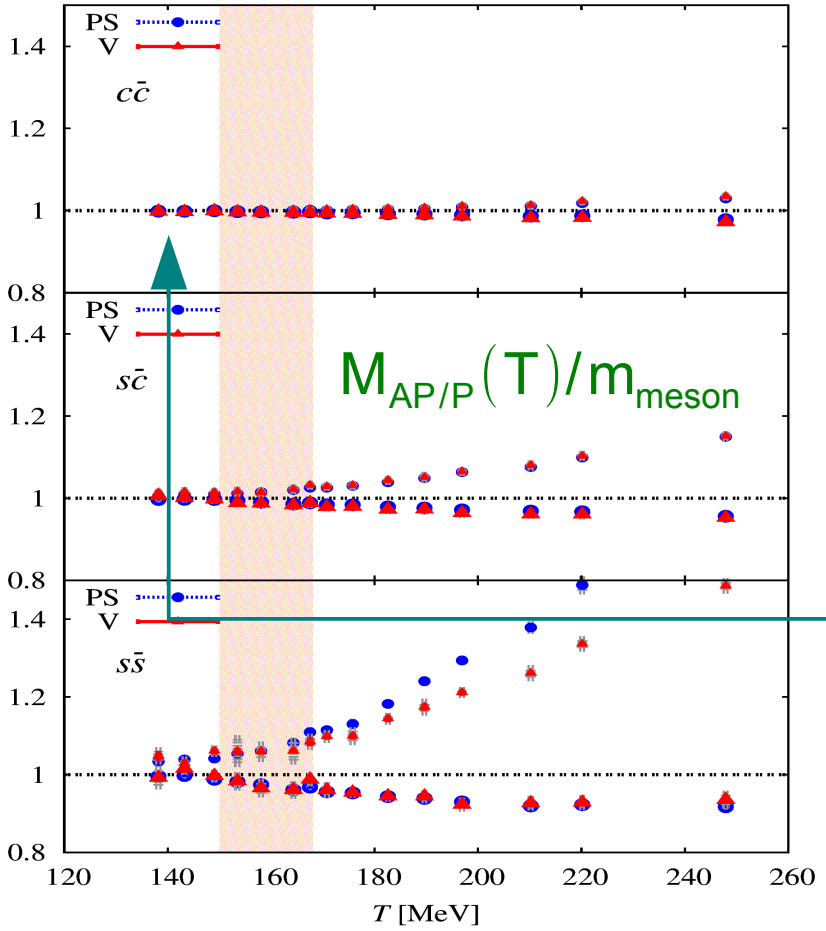
collective flow charm quarks in HIC

Charm and charmonia at high temperatures

do charmonia survive inside QGP ?

spatial correlation function & screening masses (M)

with both periodic (P) & anti-periodic (AP) temporal boundary conditions

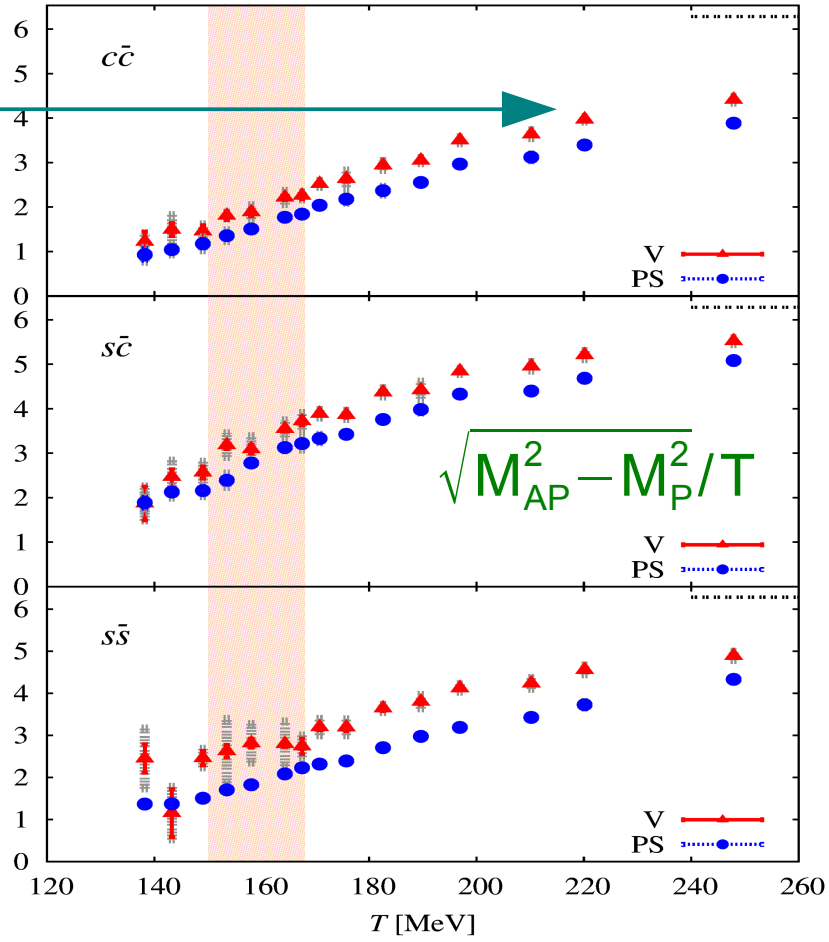


$T \gtrsim T_c$

significant modifications

$T \lesssim T_c$

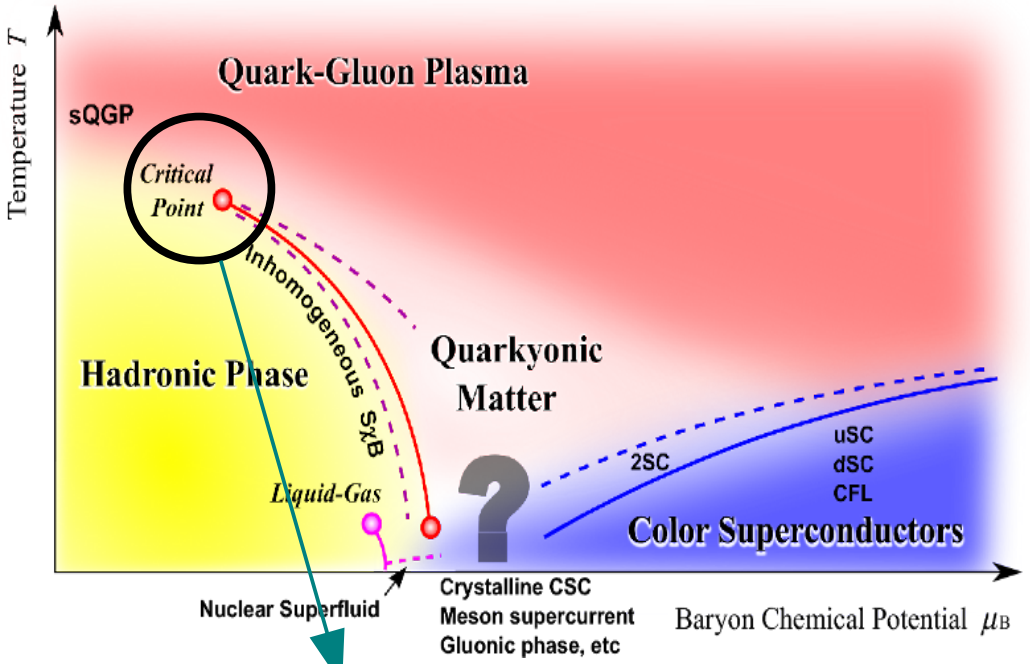
bound states?



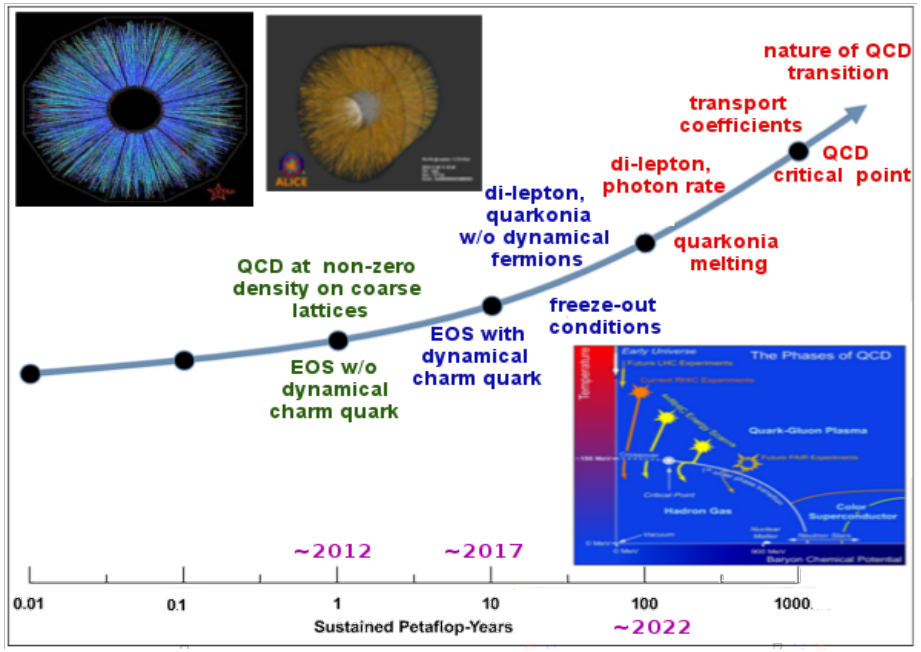
courtesy: Yu Maezawa

End note

miles to go ...



QCD critical point ?



towards exaflop computing ...

new opportunities for many more unexplored issues

… certainly demands a larger pool of brains

if you too get fascinated by extreme phases of QCD you are most welcome to help us in exploring them